PROPOSED STRATEGY TO OBTAIN OPTIMUM INTER-STATION DISTANCE FOR GPS CORS DEVELOPMENT SCENARIO

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ABSTRACT:

The critical part in the development of GPS CORS network is known as the inter-station distance between the CORS or baseline length. Due to the diversity of baseline length can be implemented for the CORS network, this paper presents an alternative strategy to obtain the optimum inter-station distance between the CORS. The optimum inter-station distance between the CORS can be achieved by analysing the quality of GPS baseline data and applying GPS CORS Optimal Prediction Number Calculator (ONPC). Three baselines have been designed with appropriate range of baseline length which short (0-30km), medium (30-70km) and long (70-180km) baselines in order to examine the quality of GPS data and GPS CORS ONPC. The GPS baseline data quality analysis presents the performance of short, medium, and long baselines in term of percentage of ambiguity resolution (AR) and separated medium of GPS distance-dependent errors. The GPS CORS ONPC shows the distribution of CORS network using the length of short, medium, and long baselines within the frame and the total cost required for the establishment of the CORS network. From the result, it is found that the short and medium baselines have superior performances in term of GPS data quality which has stated higher success rate of AR (more than 50 percent) and less than 1cm standard deviation for dispersive and non-dispersive medium of GPS distance-dependent errors compared to long baseline. However, in term of cost, the longer baseline stated the cheapest, followed by medium baseline and short baseline which is 12 times and 182 times greater than longer baselines respectively. Therefore, the medium baseline is chosen as optimum inter-station distance in the development of CORS network due to better coverage and satisfied quality of GPS data with acceptable cost.

1. INTRODUCTION

Permanent Global Positioning System (GPS) reference station often referred as GPS Continuously Operating Reference Station (CORS) nowadays has become the backbone of the infrastructure in most GPS surveying application. It enables users to correctly differentiate static GPS measurement (Botsyo et al. 2020). Many agencies, such as government, private sectors, and researchers around the globe are involve in developing the CORS facilities. In order to establish CORS, there are many aspects need to be considered, such as the suitable location for the CORS, consistency power sources, good internet coverage to transmit GPS data, special GPS hardware and software, and finally, the GPS data quality analysis at each of GPS CORS location (Shariff et al. 2009). The issue on developing CORS has been described and discussed in details by Stone (2000). Furthermore, the requirement and recommendation for the establishment and operation of GPS or Global Navigation Satellite System (GNSS) CORS are available through International GNSS Services (IGS) guidelines website (IGS, 2015) and Intergovernmental Committee on Surveying and Mapping (ICSM) publication (ICSM, 2020).

According to ICSM, CORS can be categorized into three hierarchical classes, which are tier 1, tier 2, and tier 3. The tier 1 CORS is generally established to support the IGS CORS network or other equivalent ultra-high accuracy networks for geoscientific research and global reference frame definition. While tier 2 CORS is established primarily for national CORS network in defining and maintaining national geodetic reference frames. To support tier 2 CORS network densification, tier 3 CORS is established. The implementation of denser CORS network within the region is expected to deliver higher quality GPS data to user compared to sparse CORS network. However, developing denser CORS network will incur more cost compared to developing sparse network.

Generally, there are three (3) parameters that need to be addressed in designing CORS network, which are first (1), the distance between the CORS; second (2), the connection of the CORS to the reference frame or national geodetic datum; and third (3), the effect of CORS outage on service delivery. The second and third parameters can be solved by connecting the CORS and national CORS network GPS data in the survey control network and by using good internet connection or proper selection of location with good internet coverage, respectively. Meanwhile, the first parameter in this case is critical to be assume.

In order to avoid blunders assumption on the first parameters, this paper propose an alternative strategy to define optimum inter-station distance between CORS. In this case, the optimum inter-station distance between the CORS obtained will serve as guidelines for future development of CORS network. The proposed strategy is also expected to support developers in the establishment of CORS network as well as improve the performance of CORS network to users within the coverage.

2. DETERMINATION OF OPTIMUM INTER-STATION DISTANCE BETWEEN THE GPS CORS

The methodologies to identify optimum inter-station distance are discussed in details in this section. The procedure consists of two parts, which are; first (1), GPS baseline data quality analysis; and second (2), GPS CORS Optimal Number Prediction Calculator (ONPC). The first procedure is designed to monitor the quality of GPS data towards specific baseline length. Meanwhile, the second procedure are introduced and designed to estimates the total number of CORS and cost required in the development of CORS network in a specific area. Research towards baseline assessment has been conducted to obtain the optimal baseline length for the analysis of this study.

Previous research by Okorocha and Olajugba (2014) shows the comparative analysis and significance between short (<1.5km), medium (<12km), and long baseline (<107km). The result shows that there are no significant differences in precision between short and medium baseline. Meanwhile, for the long baseline, significant difference in precision exists when compared to medium as well as short baseline. Gumilar et al. (2019) conducted an investigation towards the performance of short to long range single baseline RTK GNSS (Up to 80km) by applying modified Least-squares AMBiguity Decorrelation Adjustment (LAMBDA) method to resolve the ambiguity in carrier phase. The result shows that the percentage of AR are depends on the baseline length and the site obstruction. Meanwhile, in term of positional accuracies, the differences are within the RTK accuracy which are several centimetres up to 80km for horizontal solution while three times higher for vertical solution.

Other research has also been carried out by Musa (2007) to study the residual of dispersive and non-dispersive medium of GPS distance-dependent errors between short (25km), medium (143km), and long (339 km) baselines. The result shows that the dispersive medium for long baseline can reach up to ±130cm, ±100cm for medium baseline and ±30cm for short baseline. Meanwhile, the result for non-dispersive medium shows that the first 1 hour of observation, the residual are the smallest and almost similar for all baseline. The residuals, however, increase in magnitude when the elevation of satellite decrease. He also mentions that those designed baseline are not applicable for fast and near real-time ambiguity resolution (AR). This is due to the existences of these two effects (dispersive and non-dispersive medium), orbital and station-dependent errors, which will complicate the direct AR using L1 and L2 measurement alone in the processing.

From their experiments, it can be concluded that when the baseline is too long, the GPS dispersive and non-dispersive residual starts to increase, the performances of integer ambiguity resolution for the baseline starts to deteriorate and the positional accuracy becomes unacceptable. However, in term of cost to establish the CORS network, the longer baseline is expected to be better compare to shorter baseline due to number of CORS required to be established. Therefore, in this paper, three range of baseline length are appropriately design with ranges of 0 to 30km, 30 to 70km, and 70 to 180km baseline length for short, medium, and long baselines, respectively, using regional CORS network in Malaysia namely Malaysian Real-Time Kinematic (RTK) Network (MyRTKnet) and National Research and Development CORS Network (NRC-net). Figure 1 illustrates an overview of the baselines designed for short, medium, and long baselines using MyRTKnet and NRC-net.

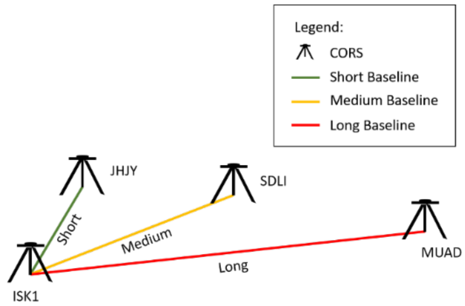

Figure 1. Short, medium and long baselines.

The range of baseline length for short, medium, and long baselines are determined to give flexibility in selecting CORS in designing the baselines. In other words, the quality of GPS data within the range are expected to be similar. Table 1 shows the length for short, medium, and long baselines.

Type of Baseline	Baseline Length (km)
Short	18
Medium	67
Long	178

Table 1. Length for short, medium and long baselines.

2.1 GPS Baseline Data Quality Analysis

The GPS baseline data quality analysis are categorized into two analyses, which are; first (1), percentage of ambiguity resolution (AR) analysis; and second (2), dispersive and non-dispersive of GPS distance-dependent errors analysis. To deliver acceptable quality outcomes for first (1) and second (2) analysis, the geodetic GNSS software processing namely Bernese GNSS software version 5.2 is utilized.

In this analysis, the GPS observation data have been collected on $1st$ August 2021 with 24 hours observation period and 30 second sampling rate for each CORS, which are ISK1, JHJY, SDLI, and MUAD. With 24 hours observation period sampled, the data provided should be sufficient enough for this type of analysis.

2.1.1 Analysis on Percentage of Ambiguity Resolution (AR): Previous study by Baroni et al. (2009) shows the comparative analysis of three different AR method namely Least-Square Ambiguity Search Technique (LSAST), Least-square Ambiguity Decorrelation Adjustment (LAMBDA) and Fast Ambiguity Search Filter (FASF) for real-time static and kinematic positioning in term of time to fix and percentage of correct ambiguity fixes. The result shows that each of these AR methods has differences performances in solving the integer ambiguities due to different manners in building the search space for float ambiguity. In order to measure the quality of baseline length in this paper, each baseline length is required to be processed with the same AR method to fairly distribute the same performance of AR algorithm for every baseline length.

By using the same AR method for each designed baselines processing in this analysis, the quality of GPS baseline data in this case can be monitored. Therefore, in the first analysis, the designed baseline namely short, medium, and long baseline are processed in Bernese GNSS software. The AR algorithm used in this processing are SIGMA-Dependent algorithm. Due to the length of medium and long baseline, the success rate of AR process for direct L1 and L2 measurement alone is impossible. However, with additional frequencies provided in each of baselines observation data, the indirect AR using wide-lane (L5) ambiguity has made it possible according to O’Keefe et al. (2009). The outcome of this analysis is the percentage of AR processing success rate.

2.1.2 Analysis on Dispersive and Non-dispersive Medium of GPS Distance-dependent Errors: Once the ambiguity has been resolved to their integer value, the dispersive and non-dispersive medium of GPS distance-dependent error for short, medium, and long baselines are generated. To generate separated dispersive and non-dispersive medium of GPS distance-dependent errors, the geometry-Free (GF) and ionosphere-Free (IF) phased-based linear combination of L1 and L2 is utilized respectively.

The generation of the dispersive and non-dispersive medium of GPS distance-dependent errors are largely depend on the first (1) analysis, which are the success rate of AR towards each baseline. To improve the quality of non-dispersive medium of GPS distance-dependent errors in this analysis, precise orbit namely final orbit and ionosphere model, which has been download from IGS product website (IGS, 2021) are utilized to minimize the effect of orbital errors (Musa, 2007) and the effect of High-Order Ionospheric (HOI) delay (Dach et al. 2015).

The approach is to partition whether there are dispersive or non-dispersive medium of GPS distance-dependent errors. The result represents the existence of dispersive and non-dispersive of GPS distance-dependent errors within short, medium, and long baselines.

2.2 GPS CORS Optimal Number Prediction Calculator (ONPC)

The aim of this part is to calculate the total number of CORS within specific area. The total number of CORS within specific area can be calculated by assuming the frame and baseline length. The frame in this case represents the desired area. In this paper, only square frame can be design. By assuming the length (x), the square frame can be drawn. Figure 2 illustrates the method to design a frame.

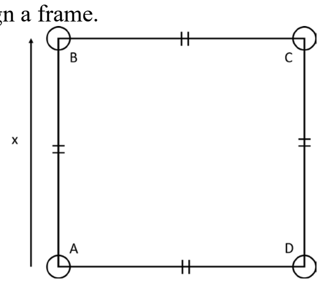

Figure 2. Design of the frame for specific area.

To design a frame, the x value is used for each corner coordinates (A, B, C and D) as shown below (Eq. 1):

$$A(0,0), B(0,x), C(x,x), D(x,0) \tag{1}$$

Once the frame has been generated, the area for the designed frame can be calculated using the coordinates. The value of x then is divided with the assigned baseline length to get initial number of CORS for row components ($CORS_{row}$) in the frame, as shown in (Eq. 2):

$$CORS_{row} = \frac{Length\ (x)}{Baseline\ Length} \tag{2}$$

The CORS coordinate within the frame can be obtain by multiplying the number of CORS with baseline length sequentially as shown in (Eq. 3):

$$EastCORS_{row}(n) = cumCORS_{row}(n) \times Baseline\ Length \tag{3}$$

where $EastCORS_{row}$ = plane CORS coordinate (Easting)
$cumCORS_{row}$ = cumulative CORS number
n = number of CORS (sequential)

To maximize the distribution of CORS within the frame, the distance between the CORS of (first and last) and boundary line must be the same. In this paper, the straight line of the CORS is drawn towards boundary line to obtain the intersection point between the straight and boundary line. The intersection point in this case is denoted as (IP_n) where n is the number of intersection point. By using coordinate of the IP_n, the distance, d can be calculated as shown in (Eq. 4) to (Eq. 6).

$$d_1 = EastCORS_{row}\ (n = 1) - IP_1 \tag{4}$$

$$d_2 = EastCORS_{row}\ (n = last) - IP_2 \tag{5}$$

$$d = \frac{d_1 + d_2}{2} \tag{6}$$

The distance, d then is added with each of CORS coordinate to obtain final CORS coordinate (Eq. 7):

$$Final\ CORS_{east,row} = EastCORS_{row}(n) + d \tag{7}$$

Since the square frame shape is design, the numbers of CORS for the row and column are the same. Therefore, the total number of CORS can be easily calculated by multiplying the number of CORS for row components ($CORS_{row}$) with their numbers as shown below:

$$TotCORS = CORS_{row} \times CORS_{row} \tag{8}$$

The GPS CORS ONPC only calculate total number of CORS inside the design frame. Once total number of CORS network has been obtained, the cost required to establish CORSs within the frame can be easily estimated by multiplying the total numbers of CORS within the frame with cost of one type geodetic GPS receiver and CORS infrastructure. The cost in this case are varies depending on the type of geodetic GPS receiver and the CORS infrastructure used at the sites. This paper only predicts the cost with assumption all of the CORS within the frame are using the same type of geodetic GPS receivers and same type of CORS infrastructure.

$$Total\ Cost\ (MYR) = TotCORS \times (Cost_{receiver} + Cost_{Infra}) \tag{9}$$

To distribute total number of CORS within the frame, the plane coordinate for each CORS is required. This paper proposed to use the programming platform to avoid erroneous in computing the final CORS coordinate during this step. This experiment will represent the distribution of GPS CORS by using the short, medium and long baseline length within the design frame along with their plane coordinates. The cost required to establish the total number of GPS CORS within the design frame as well are presented.

This contribution has been peer-reviewed.
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3. RESULT AND ANALYSIS

The result for data quality analysis of GPS baseline is presented in term of percentage of AR and separated medium of GPS distance-dependent errors for short, medium, and long baselines. Meanwhile, for the GPS CORS ONPC, the cost and distribution of CORS network using short, medium, and long baselines are presented.

3.1 Percentage of Ambiguity Resolution (AR) Analysis

The percentage of ambiguity resolution are presented for short, medium, and long baselines using the same AR method provided by Bernese GNSS software. To assist the success rates of AR processing in this analysis, this process includes the use of carrier-phased double-differenced technique, dual-frequency receiver for redundancy and linear combination, precisely known coordinate for each CORS, final orbit to minimize orbital error, and ionosphere model to reduce the effect of HOI. The process for introducing float troposphere solution is also introduced in this analysis.

Figure 3 shows the performance of short, medium, and long baselines towards AR processing. According to the results in, the short baseline indicates the highest percentage of AR, followed by medium baseline, and the long baseline with 66, 56, and 36 percent, respectively. The most significant impact on AR success rate is known as ionospheric delay or non-dispersive medium of GPS distance dependent errors.

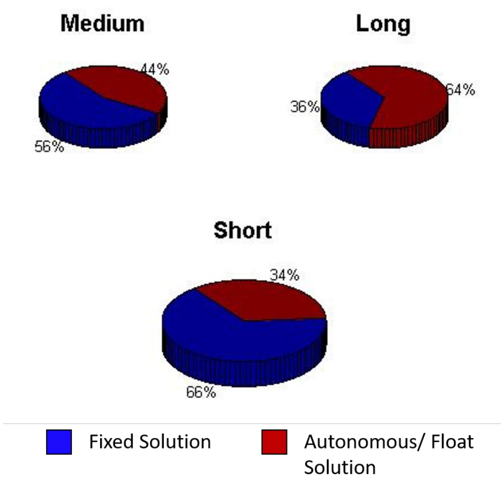

Figure 3. Percentage of AR for short, medium and ling baseline processing.

Further analysis on dispersive medium of GPS distance-dependent errors is discussed in the next sub section. To improve the success rate of AR processing, many researchers have constructed GF and IF linear combination as the order to reduce the effect of ionospheric delay during the processing such as in (Xu et al. 2015) and (Zhao et al. 2015). If the applied Network-Based Real-Time Kinematic (N-RTK) AR processor of the CORS network used is available, it is highly recommended to use it for this type of analysis. It is to improve selection of baseline as well as enhance the performance of network-based AR of the CORS network.

3.2 Dispersive and Non-dispersive Medium of GPS Distance-dependent Errors Analysis

Figure 4 show the dispersive medium of GPS distance-dependent errors using GF phased-based linear combination of L1 and L2 signal for short, medium, and long baselines, respectively. Meanwhile, Figure 5 show the non-dispersive medium of GPS distance-dependent errors using IF linear combination of L1 and L2 signal for short, medium, and long baselines, respectively.

Based on Figure 4, the results show that the variation of dispersive medium of GPS distance-dependent errors are indeed depends on baseline length. The results also show that the amount of dispersive medium of GPS distance-dependent errors increase as the baseline length increase. Compared to Musa (2007) analysis on GPS dispersive medium of GPS distance-dependent error, the value in this paper can be considered as in good condition. By referring the result on percentage of AR in the first analysis, the amount of dispersive medium of GPS distance-dependent errors within each baseline in this analysis can be the factor for the unsuccessful AR. The success rate of AR processing in the first (1) analysis are more likely depends on amount of dispersive medium in the measurement, which means the higher the volume of dispersive medium of GPS distance-dependent errors, the lower the AR success rate.

Meanwhile for non-dispersive medium of GPS distance-dependent errors, only slight difference displayed between short, medium, and long baselines compared to dispersive medium of GPS distance-dependent errors. The trend and pattern of the non-dispersive medium of GPS distance dependent errors show these three baselines are almost similar. The same result was reported in Musa (2007). It is believed that the reason behind this result also suffer from the same factors as in his analysis. Further analysis on this dispersive and non-dispersive medium of GPS distance-dependent errors are carried out through statistical analysis for validation purpose. Table 2 and Table 3 show the minimum, maximum, mean, standard deviation, and variance of dispersive and non-dispersive medium of GPS distance-dependent errors, respectively.

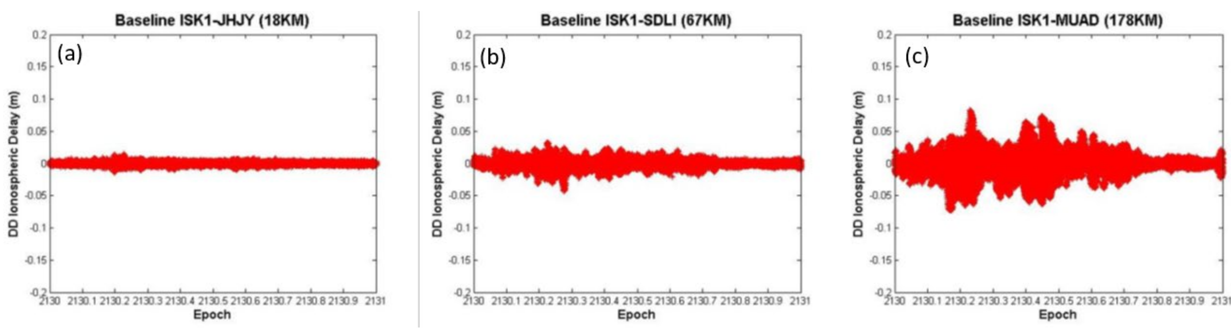

Figure 4. Dispersive medium of GPS distance-dependent errors for (a) short, (b) medium, and (c) long baselines.

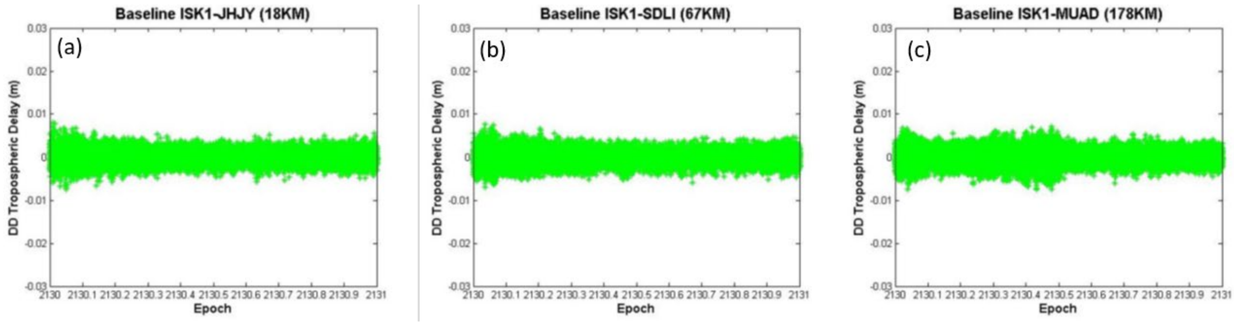

Figure 5. Non-dispersive medium of GPS distance-dependent errors for (a) short, (b) medium, and (c) long baselines.

Baseline	Min (m)	Max (m)	Mean (m)	Standard Deviation (m)	Variance (m)
Short	-0.0134	0.0148	1.8423^{-5}	0.0022	4.8369^{-6}
Medium	-0.0423	0.0323	1.8522^{-4}	0.0066	4.3281^{-5}
Long	-0.0721	0.0827	5.2438^{-4}	0.0178	3.1848^{-4}

Table 2. Statistical analysis on dispersive medium of GPS distance-dependent errors.

Baseline	Min (m)	Max (m)	Mean (m)	Standard Deviation (m)	Variance (m)
Short	-0.0074	0.0080	5.5405^{-7}	0.0015	2.1076^{-6}
Medium	-0.0070	0.0076	1.3163^{-5}	0.0015	2.3194^{-6}
Long	-0.0075	0.0071	1.6143^{-6}	0.0017	2.9204^{-6}

Table 3. Statistical analysis on non-dispersive medium of GPS distance-dependent errors.

Based on the results in Table 2, the maximum value for dispersive medium of GPS distance-dependent errors can reach up to 1.5cm, 3.2cm, and 8.3cm for short, medium, and long baselines, respectively. Meanwhile, for minimum value, the value can achieve -1.3cm, -4.2cm, and -7.2cm for short, medium, and long baselines respectively. The results indicate that the short baseline consists the smallest amounts of dispersive medium residuals, followed by medium and long baseline. The mean, standard deviation and variance dispersive medium for short, medium, and long baselines show that the dispersive medium of GPS distance-dependent errors is indeed influenced by baseline length. These condition, together with other error sources, such as non-dispersive medium of GPS distance-dependent errors and station-dependent errors is considered acceptable to solve direct L1 and L2 AR, except for long baseline due to higher in magnitude of dispersive medium of GPS distance-dependent errors, which is 1.7cm.

For non-dispersive medium of GPS distance-dependent errors, the maximum value can reach up to 8.0mm, 7.6mm, and 7.1mm for short, medium, and long baselines, respectively. Meanwhile, the minimum value can reach as low as -7.4mm, -7.0mm, and -7.5mm for short, medium, and long baselines, respectively. In this case, the medium baseline indicates the lowest amount of non-dispersive medium residual, followed by short and long baseline. However, the maximum value for each of the baselines are contrary to the dispersive medium, which the long baseline presents the lowest, followed by medium and short baseline. The mean value indicates that the residuals of non-dispersive medium for medium baseline is more active compared to short and long baselines. However, for overall 24 hours analysis, the non-dispersive medium of GPS distance-dependent errors are indeed depended on baseline length.

3.3 GPS CORS ONPC Analysis

The total number of CORS required to be established within the desired area are calculated based on the designed frame and length of short, medium, and long baselines. The frame is designed with a length of 500km. Figure 6 shows the designed frame to represent the desired area for the establishment of CORS network and for the purpose of number prediction.

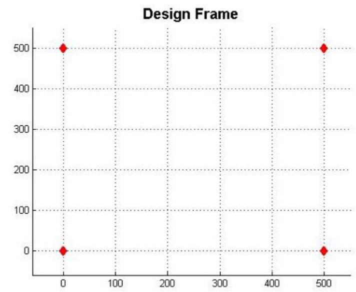

Figure 6. Design frame for the purpose of CORS number prediction calculation.

The area for the designed frame can be calculated using coordinates of each corner of the frame. The area for the frame is 250, 000km². Figure 7 show the distribution of CORS within the designed frame for (a) short, (b) medium, and (c) long baselines, respectively.

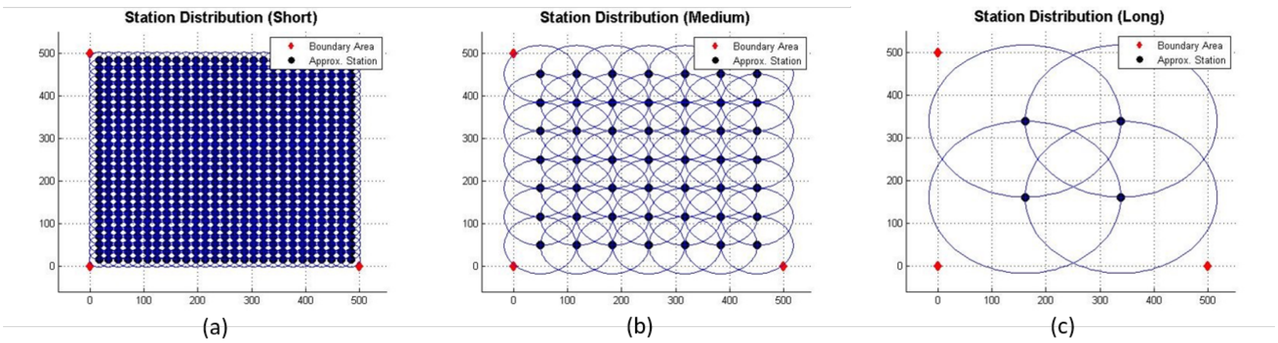

Figure 7. CORS distribution within the frame using short, medium and long baseline length.

The red diamond dots shown in Figure 7 indicate the boundary for the frames, while the black dots indicate the CORS. The blue circle shown indicates as CORS coverage area with baseline length as radius. The space between black dots is defined by the length of input baseline. Table 4 shows total distribution of CORS within the designed frame using the length of short, medium, and long baselines.

Baseline	CORS Total Number
Short	729
Medium	49
Long	4

Table 4. Total number distribution of CORS within designed frame.

In this paper, the type of geodetic GPS receiver and CORS infrastructure used for all CORS distribution within the frame are considered to be the same. The price of geodetic GPS receiver has been reviewed; the range is approximately around 80,000 Malaysian Ringgit (MYR) per unit. Meanwhile, the cost for the CORS infrastructure in this case is approximately calculated around 5,000 MYR per CORS. The cost for the establishment of CORS network within the frame are calculated by multiplying the price of the receiver with total number of distributed CORS. Table 5 shows the estimated cost for CORS network for short, medium, and long baselines.

Baseline	CORS Total Number	Cost (MYR)
Short	729	61,965,000
Medium	49	4,165,000
Long	4	340,000

Table 5. Estimated cost based on distribution of CORS network for short, medium and long baselines.

According to Table 5, the cost to establish CORS network using long baseline is the cheapest with only 4 CORS. Meanwhile, the establishment cost for CORS network using short baseline is extremely expensive compared to medium and long baselines. By implementing medium baseline for CORS network, the cost seems acceptable for the area of 250, 000km².

4. SUMMARY AND CONCLUSION

Based on data quality analysis of GPS baselines, short baseline shows the best performance on AR processing compared to medium and long baselines. Similar results are indicated in dispersive medium of GPS distance-dependent errors analysis for short baseline, which contain the lowest amounts of dispersive medium residuals. However, for the non-dispersive medium of GPS distance-dependent errors, short medium suffers higher effects compared to medium baseline. Overall, the results show the variations of dispersive and non-dispersive medium of GPS distance-dependent errors are lowest for short baseline. As a conclusion, the GPS baselines data quality has proven that the short and medium baselines are capable of delivering satisfactory quality of GPS data to the user within the coverage or baseline length with higher than 50 percent AR success rate and least amount of dispersive and non-dispersive of GPS distance-dependent errors with standard deviation less than 1cm.

The GPS CORS ONPC provide alternative way to calculate total number of CORS within designed area. By assuming the designed area in term of frame in this method along with baseline length, the total numbers of CORS can be calculated. The cost can be easily estimated once total number of CORS is known. The result shows that the CORS network using short baseline indicates the highest distribution of CORS compared to medium and long baselines. The cost to develop short baseline as inter-station distance for CORS network are however too expensive to be conducted. Contrary to long baseline of CORS network, which acquired lesser numbers in CORS distribution and demand the cheapest cost.

By using medium baseline as CORS network inter-station distance, the CORS are properly distributed within the network compared to short and long baselines, also in term of cost, it is tolerable and acceptable for the size of designed area. As a conclusion, by using short and medium baselines for CORS network inter-station distance, the network appears to have better coverage within the designed area compared to long baseline. In term of cost, long baseline is selected in the first place. Comparing medium and long baseline in term of cost, medium baseline, in this case, is still acceptable compared to short baseline, which the cost is 182 times higher compared to the cost for long baseline. Meanwhile the cost for medium baseline only required 12 times higher than the cost of long baseline. In this case the medium and long baseline are acceptable in term of the development cost of CORS network.

By using short baseline as inter-station distance for the CORS network, it is expected that the CORS can deliver the best quality of GPS data to users. However, the cost required to develop the network is way too expensive. To reduce the cost, long baseline is proposed to be set as CORS network inter-station distance. However, the quality of GPS data delivered are not acceptable based on the performance of AR and residuals (i.e., dispersive and non-dispersive medium). By implementing medium baseline length for CORS network, both coverage and cost factor can be tolerated with satisfactory quality of GPS data and acceptable cost. In this case, the medium baseline is chosen as optimum-inter station distance for GPS CORS development scenario due to satisfactory quality of GPS data dissemination and cost-effectiveness in the development of the CORS network.

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